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14. ABSTRACT

The Symposium on Biodynamics Models and Their Applications took place in Dayton, Ohio, on 26-28 October 1970 under the sponsorship of the National Academy of Sciences - National Research Council, Committee on Hearing, Bioacoustics, and Biomechanics; the National Aeronautics and Space Administration; and the Aerospace Medical Research Laboratory, Aerospace Medical Division, United States Air Force. Most technical areas discussed included application of biodynamic models for the establishment of environmental exposure limits, models for interpretation of animal, dummy, and operational experiments, mechanical characterization of living tissue and isolated organs, models to describe man's response to impact, blast, and acoustic energy, and performance in biodynamic environments.

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A MODEL TO SIMULATE THORACIC
RESPONSES TO AIR BLAST AND TO IMPACT*

E. R. Fletcher

Lovelace Foundation for Medical Education and Research
Albuquerque, New Mexico

ABSTRACT

A fluid-mechanical model of the thorax is described which has been useful in explaining biophysical mechanisms and scaling procedures applicable in assessing responses of the thorax energized by air-blast overpressures or by nonpenetrating missiles. Methods of parameter estimation are discussed. Comparisons are made between measured and computed intrathoracic pressures and chest-wall motions. The tested mammalian species are shown to divide into two approximately similar groups and the implications of this are discussed. Suggestions are made concerning possible future areas of research.

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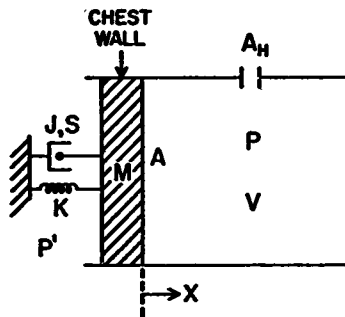
The experimental work discussed in this manuscript was conducted according to the principles enunciated in the "Guide for Laboratory Animal Facilities and Care," prepared by the National Academy of Sciences-National Research Council.

INTRODUCTION

Air-blast overpressures have been observed to produce injury and mortality in animals. For some time it has been known that when an animal is exposed to a shock wave the principal target organ (i. e., the major site of the initial injuries) is the lung.¹⁴ Starting in 1963, personnel of the Lovelace Foundation for Medical Education and Research have in a series of papers^{8,2,3,4} reported the development, refinement, and applications of a fluid-mechanical model of the thorax. This model has been useful in explaining biophysical mechanisms and scaling procedures applicable in assessing responses of the thorax energized by air-blast overpressures or by nonpenetrating missiles. The objective of this paper is to review the accomplishments to date (by summarizing the earlier papers and by reporting more recent studies) and to suggest in which areas future efforts might profitably be directed.

THE MODEL

Figure 1 shows a somewhat modified version of the model as it was envisioned to assess responses of the thorax to air blast. The complex airways and lungs of an animal are approximated by a simple orifice opening into a single chamber containing only gases. The chest wall is approximated by a rigid mass attached to a spring simulating tissue elasticity and attached to a dash pot simulating frictional effects. Clearly one could reasonably expect to simulate only the gross fluid-mechanical responses of the lung with such a simplified model. However, it was thought from the start that this modified spring-mass system could, by a proper choice of



- | | |
|---|--|
| A : Effective area | P : Internal air pressure |
| A_H : Effective orifice area | P' : External air pressure |
| M : Effective mass | K : Spring constant |
| V : Gaseous volume of lungs | J : Damping factor |
| X : Displacement | S : Power of velocity to which the damping force is proportional |
| V_0 : Gaseous volume at zero displacement | |
| γ : Polytropic exponent for gas in lungs | t : Time |

MODEL EQUATIONS

$$M \frac{d^2 X}{dt^2} + J \left| \frac{dX}{dt} \right|^S \frac{dX}{dt} + KX = A(P' - P)$$

$$\frac{dP}{dt} = -\gamma \frac{P}{V} \frac{dV}{dt} + \frac{1.334 \times 10^7 A_H}{V} |P' - P|^{1/2} \frac{P' - P}{|P' - P|} \quad \text{cgsu}$$

$$V = V_0 - AX$$

Fig. 1. Mathematical model of the thorax (incorporating a single gaseous volume) to simulate fluid-mechanical responses to rapid changes in environmental pressure.

parameters, be made to oscillate when it was engulfed by a blast wave in the same manner that intrathoracic pressures had been observed to oscillate in animals subjected to air blast.^{5, 12} This was later shown to be the case.

The model in Fig. 1 differs from the original model^{8, 2} in two respects:

(1) The damping force (see first equation in Fig. 1) is assumed to be proportional to the piston velocity to the S power, where any positive number may be chosen for S , while in the original model only a value of 1.0 could be used.

(2) A single piston is used, while the original model contained two pistons, one to simulate the chest wall and one to simulate that part of the abdomen which moves with the diaphragm. However, the values of the parameters for the original model were always (except in the first paper⁸) chosen in such a way that the two pistons moved exactly together so that in effect there was only one piston. (In the later version of the model³ the abdominal piston was omitted because reported acoustic data indicate that the motion of the abdomen is much slower than that of the chest wall.)

In all other respects (such as the assumptions that [1] the spring is linear and [2] the pressure-volume changes in the lung are polytropic) the two models are identical. We can thus use Fig. 1 in discussing calculations made with the original model provided we assume S to be equal to 1.0.

The equations in Fig. 1 can be used to compute the motion of the piston, the gas flow through the orifice, and the internal pressure as functions of time for a specified blast wave. Solving these equations

requires the use of numerical techniques and is most easily accomplished with the aid of an electronic computer. Before this can be done, however, it is necessary to have estimates of the magnitudes of A , A_H , M , V_0 , γ , K , J , and S (see Fig. 1).

PARAMETER ESTIMATION

Many sources and kinds of information have been examined in trying to estimate numerical values for the required animal parameters, and these have been discussed in the previous model papers. Among others, we have considered (1) measured gaseous lung volumes and lung masses, (2) experiments in which either an entire cat or dog was exposed to a sinusoidal pressure wave or such a wave was introduced into the airways of the animal, (3) rapid-decompression tests on man, (4) illustrations showing cross-sections of cadavers, and (5) measured intrathoracic pressures in rabbits and a dog exposed to blast waves. As might be expected, some of the parameters (listed in Fig. 1) could be estimated for one species of mammal while others could be estimated for other species. Thus in order to have an estimate of all the parameters for one species, it became necessary to scale some of the parameters from one species to another. This interspecies scaling was accomplished by using dimensional analysis and by assuming that all mammals are "similar" in that they have the same shape and equivalent distributions of various physical parameters.² It is interesting to note that all of the conclusions reached in regard to scaling between mammalian species agree with what could be predicted if we assumed the various species had "electrodynamical similitude."⁶ The basic criteria for this

similitude are a constant shape and density, and a constant propagation velocity of electromagnetic waves in all of the species. The similarity law, which is derived from these criteria, can be expressed in the following form:

A physical quantity which has the dimensions
 $(\text{mass})^\alpha (\text{length})^\beta (\text{time})^\mu$ will vary among
electrodynamically similar animals as
 $(\text{body mass})^{\alpha + \beta/3 + \mu/3}$.

Guerra and Günther⁶ have found this scaling to hold approximately, although they determined from the periods of biological functions in various species that 0.31μ was the "most probable value" in the exponent of body mass rather than the $\mu/3$ predicted by theory.

Having obtained (with the aid of interspecies scaling) estimates of all the animal parameters as functions of body mass, the model (Fig.1) was used to compute intrathoracic pressures in animals exposed to shock waves. These computed pressure waves were then compared to the measured waves, and it was found that by making moderate adjustments in the estimated animal parameters, reasonable agreement could be obtained between theory and experiment. Figure 2 shows measured and computed intrathoracic pressures for a rabbit exposed near the closed end of a shock tube to the indicated blast wave. Note that both the computed and measured internal pressure waves oscillate around the external pressure, and that the frequencies and the amplitudes of the oscillations in the two waves are in good agreement.

Intrathoracic pressure records undoubtedly represent the best single source of information for estimating the effective or average

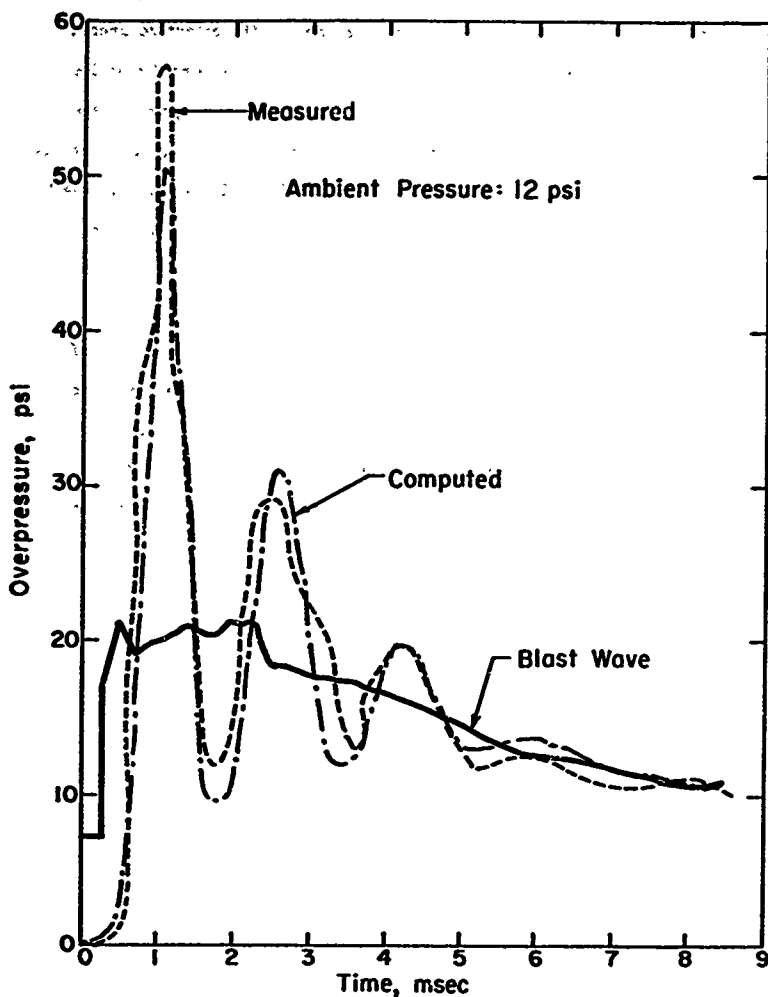


Fig. 2. Measured and computed intrathoracic overpressures for a rabbit exposed near the closed end of a shock tube to the indicated blast wave.³³Taken from Reference 2.

animal parameters needed in the model. This is because, by looking at the internal pressure records, we are seeing the effective areas, masses, volumes, spring constants, and damping factors "in action," so to speak, in the very circumstances we are trying to approximate with the model, namely an animal's being exposed to an air-blast wave. It should, however, be realized that the fact that only relatively small adjustments were required in the initial estimates of the animal parameters in order to obtain good agreement between the measured and computed intrathoracic pressures does not mean that all of those animal parameters have been "closely" determined. The effects of varying one parameter can to some extent be counterbalanced by an appropriate adjustment in another parameter. Also, the computed internal pressure records have been found to be quite insensitive to the values of some of the parameters. Let us consider in particular three facts that we have been able to determine by solving the model using various animal parameters:

- (1) The response of the thorax when energized by air-blast overpressures is so fast (see Fig. 2) that there is not enough time for a significant amount of air to flow in or out of the orifice, A_H
- (2) Because the air is essentially trapped in the lungs during exposure to air blast (see statement 1), there is a nonlinear "air spring" acting on the piston, and the effective air-spring constant is much larger than the tissue-spring constant, K .
- (3) The computed internal pressures are highly dependent on the power, S , of velocity to which the

damping force is assumed to be proportional.

However, the four intrathoracic pressure records that have been published to date (three recorded in rabbits^{8,2} and one in a dog³) provide insufficient data to determine if S actually has a value of 1.0 as has always been assumed.

An attempt has been made to determine a numerical value for the parameter S by using a group of unpublished intrathoracic pressure records¹² for several species exposed to approximately square-wave overpressures. In order to do this the model was solved many times using various overpressures and animal parameter values. In view of the facts listed above and in order to simplify the calculations, A_H and K were set equal to zero, and γ was always assumed to be equal to 1.2, the average of the polytropic exponents for isothermal and adiabatic processes for air.* For these conditions it can be shown (using the equations in Fig. 1) that if S is equal to 1.0, the peak internal overpressure in atmospheres is a function of only two quantities:

*No accurate intrathoracic temperature measurements have been made in animals during exposure to air blast. Because of the enormous heat capacity of water and the vast surface area between pulmonary gas and tissue, the pressure-volume changes may not be adiabatic. To date, none of the model calculations have required that the compromise γ of 1.2 be changed in order to approximate the data. This is not proof, however, that a γ of 1.2 corresponds to reality in the lungs, and more theoretical and/or experimental effort is needed to resolve this issue.

the external overpressure in atmospheres and a scaled damping factor, α_0 , which is equal to $(J/2A) (V_0/1.2 \text{ MP}_0)^{1/2}$. It can be demonstrated² that α_0 is equal to the damping ratio (i. e., the damping factor divided by the critical damping factor) for small oscillations (i. e., small enough that the air spring is essentially linear) about the ambient pressure, P_0 . The computed curves of constant α_0 are shown in Fig. 3 as a function of the external overpressure and the difference between the peak internal pressure and the external pressure. The time, t_m , to peak internal pressure multiplied by the quantity $A (P_0/V_0 M)^{1/2}$ can also be expressed as a function of the same two parameters which define the peak internal overpressure in atmospheres; t_m when scaled in this manner is given the symbol Z , and curves of constant Z are also shown in Fig. 3.

The data in Fig. 3 were plotted using the measured external, peak internal, and ambient (12.0 psi) pressures. These data were obtained with animals either located (1) against the end-plate of a closed shock tube (in which case the external pressure was taken to be the reflected pressure) or (2) in a shallow chamber in the side of an open shock tube (in which case the external pressure was taken to be the incident pressure). It was earlier assumed² and it can be predicted using the electrodynamic similitude law that α_0 should be constant for similar animals (at a constant P_0); this follows from the fact that α_0 is dimensionless. From Fig. 3 it can be seen that although all the data seem to line up fairly well, except for the monkey point, these data could not be reasonably approximated by a curve of constant α_0 . At the low pressures the data correspond to an α_0 of about 0.3 while at the higher pressures they correspond to an α_0 of

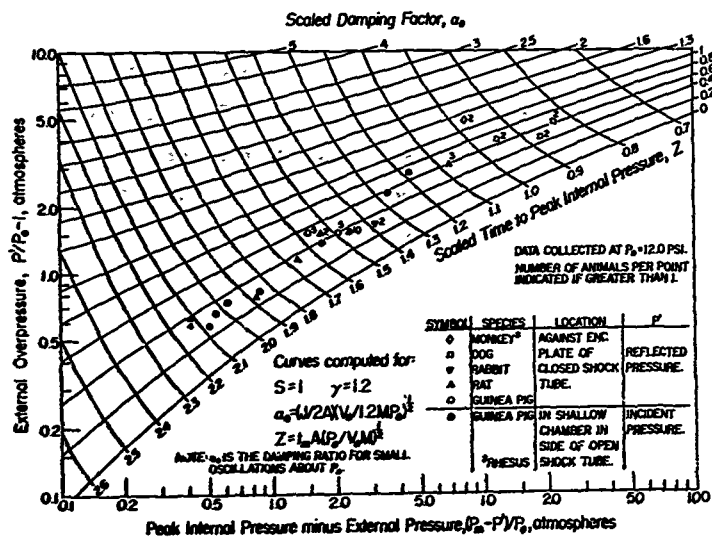


Fig. 3. Peak internal pressure minus external pressure vs external overpressure for animals exposed to a long-duration shock wave. The scaled time to peak internal pressure and scaled damping factor curves were computed with the model by assuming the damping force to be proportional to piston velocity.

about 0.6. As would be expected, the α_0 's that have been used in previous papers lie in this range.

Since the data do not correspond to a constant α_0 as has been predicted for S equal to 1.0, it was decided to assume an S of 2.0 (i.e., a damping force proportional to velocity squared) in order to see if the data would then fit the predictions. The model solutions that were made for $S=1.0$ were repeated with the only change being that S was set equal to 2.0. The scaled damping factor, E , is then equal to (JV_0/AM) which cannot be interpreted in terms of a damping ratio as was done for $S=1.0$ *. The scaled time, Z , has the same form for $S=2.0$ as it did for $S=1.0$. Figure 4 shows the results of the calculations for $S=2.0$ and the data shown on Fig. 3 are also shown on Fig. 4. Since E is dimensionless, the data should fall along a curve of constant E . We can see, however, that at the low pressures the data correspond to an E of 2.0 and at the high pressures to an E of 1.0 (excluding the monkey data). Thus once again the data do not fall along a curve of constant scaled damping factor, but they do cut across the E curves in the opposite sense from the way in which they cut across the α_0 curves. For this reason it seemed that in order to have the data fall along a curve of constant scaled damping factor, a value of S between 1.0 and 2.0 would have to be chosen. Therefore, the model calculations were repeated for $S=1.5$, and the data and predicted curves are shown in Fig. 5. The dimensionless scaled

*When S is greater than 1.0, the damping ratio is effectively zero for small oscillations and varies with the peak piston displacement (even with a linear spring) for larger oscillations.

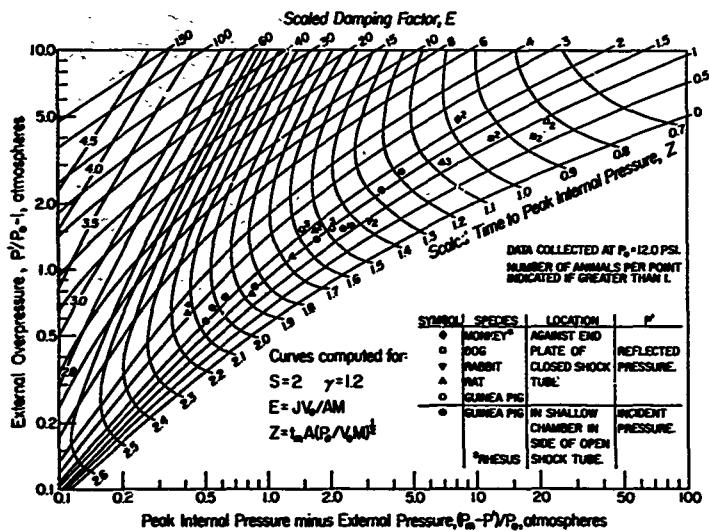


Fig. 4. Peak internal pressure minus external pressure vs external overpressure for animals exposed to a long-duration shock wave. The scaled time to peak internal pressure and scaled damping factor curves were computed with the model by assuming the damping force to be proportional to piston velocity squared.

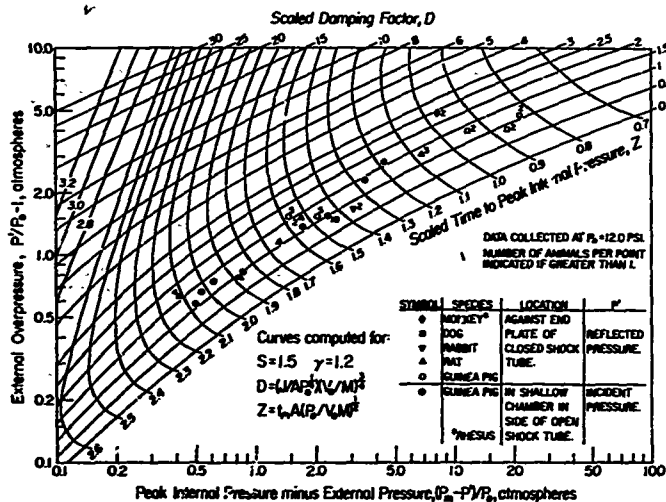


Fig. 5. Peak internal pressure minus external pressure vs external overpressure for animals exposed to a long-duration shock wave. The scaled time to peak internal pressure and scaled damping factor curves were computed with the model by assuming the damping force to be proportional to piston velocity to the 1.5 power.

damping factor, D , is equal to $(J/A) (V_0/M)^{3/4} P_0^{-1/4}$ and the scaled time, Z , has the same form as before. For $S=1.5$ the data do, as predicted, seem to fall along a curve of constant D with a value of $D=1.3$ being the estimated best fit to the data. The rhesus monkey data, however, fall at a D value of about 2.4. Since this point represents only two tests (both at essentially the same external overpressure), the possibility of some error should not be entirely ruled out, and it would therefore be premature to try to speculate as to the cause of this anomaly. If the point is substantiated, it would mean that for a given external overpressure the peak internal pressure would be considerably smaller in a rhesus monkey than it would be in any of the other four species tested.

Having concluded that the peak internal pressure can be reasonably predicted by choosing $\gamma=1.2$, $S=1.5$, and $D=1.3$, the next step is to consider the time to peak internal pressure. The actual times were determined from the intrathoracic pressure records by considering both the time when the internal record first moved above zero and the time when the external pressure wave struck a second gauge (which was triggered at the same time as the intrathoracic gauge) mounted in the side of the shock tube at a known location with respect to the animal. The scaled times were estimated from the Z lines and the data points on Fig. 5. It can be seen, however, that if Fig. 3 or 4 had been used, these scaled times would not have been very different. Point by point the actual time to peak pressure was divided by the scaled time to peak pressure and the resultant values of t_m/Z for each species showed no systematic variation with incident

or peak internal pressure. Therefore, the values were averaged for each species,* and these averages are shown in Fig. 6 plotted against mean body mass of the animals. From considerations of dimensional analysis or the electrodynamical similitude law it can be predicted that t_m/Z should vary as animal body mass, m , to the $1/3$ power, and indeed the points on Fig. 6 can be reasonably approximated by the equation $t_m/Z = 0.6 (m/\text{kg})^{1/3} \text{ msec}$.

To summarize, we have found that for dogs, rabbits, rats, and guinea pigs exposed to square-wave overpressures it is possible to reasonably estimate the peak internal pressure and time to peak while not violating the laws of dimensional analysis or the electrodynamical similitude law by choosing:**

$$K = 0, A_H = 0, \gamma = 1.2, S = 1.5,$$

$$(J/A) (V_0/M)^{3/4} (12 \text{ psi})^{-1/4} = 1.3,$$

$$\text{and } (1/A) (V_0 M / 12 \text{ psi})^{1/2} = 0.6 (m/\text{kg})^{1/3} \text{ msec}.$$

However, more data are needed, and the calculations should be repeated for other values of γ . It is interesting to note that in order to predict the correct peak pressure and correct time to peak it is not

*Since the guinea pigs were tested in two locations in the shock tube, a separate average was computed for each location.

**The 12-psi value appears in the following equations because this was the ambient pressure where the data were collected. The 1-kilogram value and the msec unit are included to keep the equations dimensionally correct. Care should be taken in using these equations to keep the units consistent.

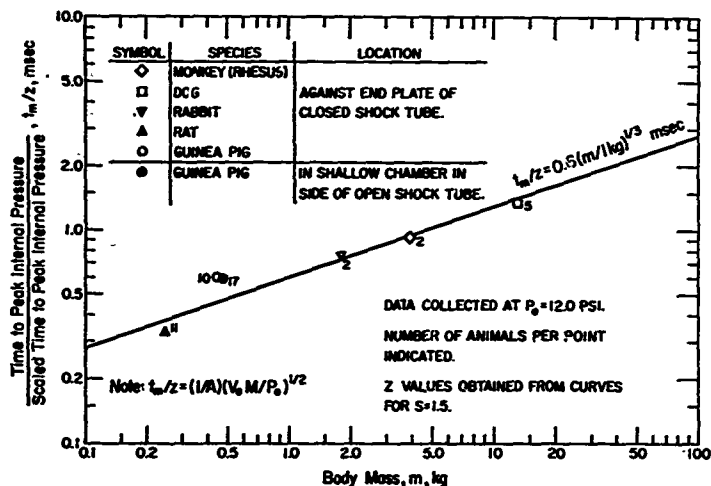


Fig. 6. Time to peak internal pressure divided by scaled time to peak internal pressure vs body mass for animals exposed to a long-duration shock wave. The scaled times were computed with the model by assuming the damping force to be proportional to piston velocity to the 1.5 power. The line is an estimated best fit to the data with the theoretical slope of 1/3.

necessary to have good estimates of J , A , V_0 , and M separately, but it is necessary to have good estimates of $(J/A) (V_0/M)^{3/4}$ and $(1/A) (V_0 M)^{1/2}$.

PRIMARY BLAST APPLICATIONS

As was mentioned earlier, the thorax model was first developed to study the consequences of exposure to blast-induced variations in environmental pressure (i.e., primary blast effects). In that regard, the ability of the model to duplicate intrathoracic pressures (see previous section) during such exposure strongly suggests that we understand the gross mechanisms which produce those pressures. The question is: How can we use this model to predict levels of injury and mortality and, hopefully, to increase our understanding of how the various pressures and motions precipitate the observed¹⁴ wounds? As a first step toward answering this question, we should see if the available mortality data are consistent with the predictions for interspecies scaling as derived from dimensional analysis or electro-dynamical similitude concepts. If this turns out to be true, we can reasonably assume that similar mechanisms are producing similar injuries in the various species; if this can be assumed, the data for all of the species can be considered in estimating injury in any one of the species, and this should considerably reduce the amount of experimental and theoretical (obtained with the model) data needed to predict and explain injury mechanisms, types, and levels. If, however, the data and the predicted scaling relationships do not agree, there can be little hope for using the model to estimate injury levels in some species (like man) that has not been systematically subjected to a

variety of blast waves in the laboratory.

A considerable amount of data, most of which has been published previously,⁴ is available on mortality in animals exposed near a normally reflecting surface to shocked blast waves whose durations ranged from 0.24 to 400 msec. It was found⁴ that for each duration and species a linear relationship existed between the probit of mortality and the logarithm of the peak reflected overpressure, and that (except for the guinea pig) all the lines had a common slope. By using this approach, the overpressures required to produce 50 percent mortality were estimated from the data for the various durations and species tested. These LD₅₀ values are plotted in Fig. 7, and curves, which were estimated by eye, have been drawn to connect the data points for each species (if there was more than one point for that species). As would be expected, the curves indicate that the required pressure increases with decreasing duration and approaches a constant value with increasing duration. It is difficult to conclude much about interspecies scaling from this plot, or to estimate where the curve for an untested species should fall. However, it can be noted that the curves do seem to be roughly divided into two groups, although the curve for the squirrel monkey extends into both groups, and the datum for the chicken (the only non-mammal tested) falls below all of the other data.

Using dimensional analysis it has been predicted² that the data for all species should fall approximately on a single curve if the LD₅₀ overpressure were plotted as a function of duration divided by animal body mass to the 1/3 power rather than as a function of duration alone. The data (from Fig. 7) have been plotted in this way

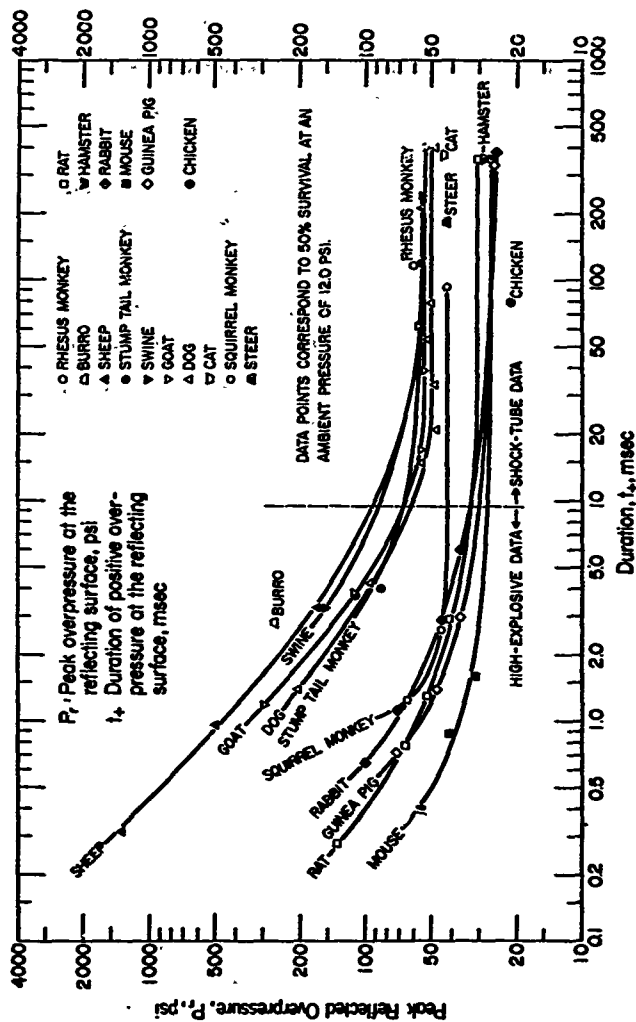


Fig. 7. Peak reflected overpressures and durations for sharp-rising blast waves which will result in 50 percent mortality in various species. The curves were estimated by eye.

in Fig. 8, and the overpressures and durations have been multiplied by the appropriate factors to make them directly applicable to a 70-kg animal (i.e., an animal the size of man) and an ambient pressure of 14.7 psi. In other words, if we assume that any one of the species tested is similar to man (the meaning and consequences of animal similitude having been discussed earlier from the points of view of dimensional analysis and electrodynamics), then the data in Fig. 8 for that species may be assumed to apply directly to a 70-kg man at sea level. Since it is apparent from Fig. 3 that all of the mammals tested are not approximately similar to each other, some discretion must be exercised in applying these data to man. The mammals do, however, seem to divide into two approximately similar groups which have been broadly designated in the figure as "small mammals" and "large mammals," even though some of the species classified as small mammals have a greater mass than some of the species classified as large mammals. Note that although the shock-tube data point for squirrel monkeys is lower than the data points for any other large mammal, it is certainly high enough to indicate that the squirrel monkey should be considered as a large mammal. The reason why the two high-explosive data points (marked by arrows) for squirrel monkeys fall so far below the rest of the data for the large mammals is not known at this time. Since these two points represent a total of only 16 monkeys, it would be premature to conclude that for some reason the overpressure tolerance of squirrel monkeys rises more slowly with decreasing duration than it does for other mammals.

In an earlier report⁴ it was concluded that a family of curves which adequately fit the data for the various species could be obtained

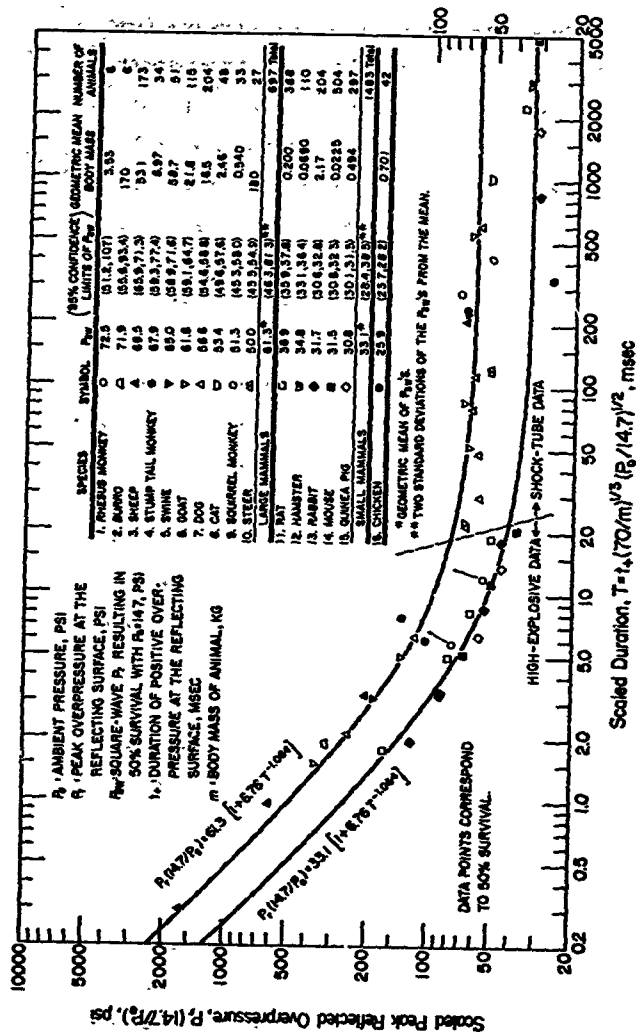


Fig. 8. Scaled peak reflected overpressures and scaled durations for sharp-rising blast waves which will result in 50 per cent mortality in various species. The curves, computed for a hypothetical average large mammal and a hypothetical average small mammal, were derived from Reference 4.

by translating (in Fig. 8) a single curve in the vertical direction only. Thus, a family of curves could be drawn in Fig. 8 for the various species which would differ by only one parameter; namely, the scaled overpressure that each curve approaches for long-duration blast waves. This scaled overpressure, P_{sw} , is listed in the figure (along with 95 percent confidence limits) for each species. It should be noted that P_{sw} is the square-wave (or long-duration) overpressure which will result in 50 percent mortality for an ambient pressure of 14.7 psi. Listed in Fig. 8 are approximate 95 percent confidence limits for the P_{sw} of an untested species which is known to belong to one of the two groups. From these limits it can be seen that the P_{sw} 's of the small and large mammals differ significantly even though there is scatter in both groups, and that the P_{sw} of the chicken is significantly below those of the mammals. The geometric averages of the P_{sw} 's for the large and small mammals are 61.3 and 33.1 psi, respectively. The two curves in the figure can be thought of as applying to a hypothetical average small mammal with a P_{sw} of 33.1 psi, and a hypothetical average large mammal with a P_{sw} of 61.3 psi. The equations for the curves were taken from Ref. 4. It is instructive at this point to quote from this reference as to how a curve was estimated for man: "To which of the blast-tolerance groups formed by the experimental animals is man likely to belong? Previous estimates place him in the high-tolerance group. Assuming that man is a member of this group but lacking further evidence, his tolerance was arbitrarily but tentatively taken to be the geometric mean of those for the members of his group...." (Thus, man has been assumed to correspond to the hypothetical average large mammal for which a curve was drawn in

Fig. 8.) This would still seem to be the best procedure for estimating the blast tolerance of a mammalian species for which a P_{sw} has not been established provided there is reasonable evidence to suggest that the species is similar to the members of one of the two groups. Several possible sources for evidence of this type will be discussed later.

Having determined that in regard to lethality there are two groups of approximately similar mammals instead of one, there is some question as to what influence this will (or should) have on our attempts to use the model to predict and explain injury mechanisms, types, and levels. We might, for instance, assume that similar mechanisms are producing similar injuries in the species of each group taken separately, but that the mechanisms and injuries for one group have nothing to do with those for the other. This would not be reasonable, however, because:

- (1) The same types of injuries have been observed in species of both groups.¹⁴
- (2) The data for both groups fall along the same curves in Figures 5 and 6.
- (3) The curves for both groups have the same shape in Fig. 8, and the same scaled time, T , applies to all species.

It, therefore, seems more reasonable to assume that the same mechanisms and types of injuries occur in both groups of mammals, even though the blast load required to produce a given level of injury varies between the groups. In terms of the model, it is to be hoped that observed injury (or mortality) levels in mammals can be correlated

with some physical quantity that can be computed with the model, such as peak piston velocity, peak internal pressure, impulse under the internal pressure wave, etc. If such a physical quantity can be found for one species, the value of the quantity required to produce a given level of injury can probably be scaled (by the methods discussed) to other species in the group of which the first species was a member. Further, the same physical quantity could probably be used to predict injury levels for the other group, and be scalable in the same way among the species of that group, but it is to be expected that the quantity might not be scalable between groups.

To date, only a limited number of calculations have been performed in an attempt to determine a physical quantity which can be computed with the model and which correlates well with mortality. A more complicated version of the thorax model was used in this study³ (see Fig. 9) which has a separate chamber for each lung and three pistons, the outside ones representing the chest walls and the middle one the mediastinal tissue between the lungs. (The nonpenetrating missile shown in the figure was disregarded for the air-blast calculations, but it will be discussed later.) By having the two lungs separated, it was hoped that the relative damage to each lung could be estimated. When the model was used to compute the pressures in a dog exposed to an LD₅₀ square-wave overpressure at the end-plate of a closed shock tube, the average of the predicted pressures in the two lungs agreed well with the measured intrathoracic pressures. It was determined that a peak internal pressure of approximately 250 psi (for a P₀ of 12.0 psi) was required to produce 50 percent mortality, and that the peak pressure in the lung against the end-plate should be